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A DESI DR1 Radial-Velocity Search for Dark Compact Companions: A Strong but Unconfirmed Candidate Around a dM0 Star

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ABSTRACT

We present a conservative, fully reproducible search for radial-velocity (RV) variability in the public Dark Energy Spectroscopic Instrument (DESI) Data Release 1 (DR1) Milky Way Survey. Using only per-epoch RV measurements, we identify stars whose velocity variability is both highly significant and robust under leave-one-out tests. A "negative space" validation pipeline then rejects ordinary luminous companions using Gaia DR3 astrometry, WISE infrared photometry, GALEX ultraviolet imaging, TESS and ZTF time-domain photometry, deep Legacy Survey imaging, and archival X-ray and radio catalogs.

One system, Gaia DR3 3802130935635096832 (DESI TargetID 39627745210139276), emerges as the most extreme survivor. DESI provides four RV epochs spanning 38.9 days with a maximum catalog RV span $\Delta\mathrm{RV}_{\mathrm{max}} \approx 146$ km s^{-1}. Using the DESI DR1 formal per-epoch RV uncertainties, a constant-RV model is rejected at $\Delta\chi^2 \approx 2.7 \times 10^4$ (DESI-only); later per-exposure reanalysis indicates the formal errors can be underestimated (i.e. reduced chi-squared $\chi^2_\nu \gg 1$), but the large-amplitude variability remains.

A key forensic update is that Gaia DR3 resolves a neighbor at $\rho \simeq 0.69''$ with $\Delta G \simeq 2.21$ mag, implying a G-band flux ratio $b_G \simeq 0.13$ and requiring blend-aware validation. We perform blend-aware remeasurement of the DESI spectra using PHOENIX templates and physically motivated flux-ratio priors; the large RV swing persists across these remeasurements.

We then resolve the origin of previously observed arm-split pathologies by downloading per-exposure, per-camera DESI spectra (DR1 `cframe` products) and remeasuring RVs as a function of wavelength region. Same-night exposures (15 minutes apart) reveal that the full Z-arm RV is unstable when sky-dominated wavelengths (9000–9800 Å) are included, while the Ca II triplet window (8500–9000 Å) yields stable and repeatable behavior. Using only this empirically "trusted" window, we recover a large RV swing $\Delta\mathrm{RV} \approx 151.2$ km s^{-1} (from -85.6 to $+65.6$ km s^{-1}). In the same-night pair, trusted-window RVs are higher than the DESI catalog values by ~ 25 km s^{-1}, consistent with the unstable sky-dominated red end biasing the catalog solution.

Finally, we verify Gaia astrometric quality metrics via a direct query to `gaiadr3.gaia_source` (script: `scripts/verify_gaia_metrics.py`), finding RUWE = 1.954 and astrometric excess noise $\epsilon_{\mathrm{AEN}} = 0.90$ mas (16.5σ significance; Gaia field `astrometric_excess_noise_sig`) at $G = 17.273$. These values indicate a poor single-source astrometric fit consistent with unresolved astrometric complexity (orbital motion and/or duplicity), but are not uniquely diagnostic given the resolved neighbor. We classify Gaia DR3 3802130935635096832 as a *strong but unconfirmed* dark compact companion candidate: the RV swing persists under conservative, windowed, per-exposure analysis, but a definitive dynamical mass claim requires follow-up spectroscopy and/or high-angular-resolution imaging to separate the blended components.

Keywords: Radial velocity(1332) — Compact objects(288) — M dwarfs(982) — Spectroscopy(1558)

1. INTRODUCTION

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Quiescent compact objects—white dwarfs (WDs), neutron stars (NSs), and stellar-mass black holes (BHs)—are expected to be abundant in the Milky Way but are difficult to detect when not accreting or otherwise luminous. Radial velocities provide a purely gravitational discovery channel: a compact companion can induce large reflex motion in an ordinary star while contributing negligible light. Modern multi-epoch spectroscopic surveys are therefore natural hunting grounds for unseen companions.

DESI DR1 provides per-epoch RVs for millions of stars in the Milky Way Survey. While DESI was not designed as a time-domain survey, the combination of multi-epoch coverage, high spectral resolution, and uniform data processing enables a systematic search for RV outliers. In this work we:

1. define conservative RV-variability metrics that are robust to outliers;
2. scan the DESI DR1 Milky Way Survey for high-significance RV variables;
3. apply a multi-wavelength "negative space" filter that searches for *gravity without light*;
4. perform targeted orbital and forensic analyses of the strongest surviving candidate, including blend-aware remeasurement and per-exposure wavelength-region truth filtering.

All analysis scripts, configuration files, and machine-readable products are publicly available at https://github.com/simulationstation/DESI-BH-CANDIDATE-SEARCH.

2. DATA SETS

2.1. *DESI DR1 Milky Way Survey*

We use per-epoch DESI DR1 Milky Way Survey RVs from the `main-bright` and `main-dark` programs. For each epoch we extract:

- heliocentric radial velocity RV_i (km s^{-1});
- formal RV uncertainty $\sigma_{\mathrm{RV},i}$ (km s^{-1});
- modified Julian date t_i (days);
- DESI `TARGETID`;
- Gaia DR3 `SOURCE_ID` when available.

For forensic validation of wavelength-dependent systematics, we additionally download per-exposure, per-camera spectra from the DESI DR1 `cframe` products for the four relevant exposures (EXPID 114768, 120194, 120449, 120450), enabling RV remeasurement in user-defined wavelength windows. These `cframe` products provide flux and inverse-variance arrays at the camera level (e.g. R and Z arms) before multi-camera combination.

2.2. *LAMOST archival spectroscopy*

We identify two public LAMOST spectra (ObsIDs 437513049 and 870813030) of the target. These spectra robustly support an early-M dwarf classification for the dominant light source. However, independent RV remeasurement of these spectra is internally inconsistent across methods (FITS-header values vs CCF refits and wavelength-split CCF), so we treat LAMOST RVs as *non-decisive* for orbit fitting and retain LAMOST primarily as a spectral-type constraint.

2.3. *Gaia DR3 astrometry and duplicity*

We verify the key Gaia DR3 quality metrics via a direct `astroquery.gaia` query to `gaiadr3.gaia_source` (script: `scripts/verify_gaia_metrics.py`).

Table 1. Verified Gaia DR3 astrometric metrics for Gaia DR3 3802130935635096832.

Quantity	Value
Gaia G magnitude	17.273
Parallax ϖ (mas)	0.12 ± 0.16
RUWE	1.954
Astrometric excess noise ϵ_{AEN} (mas)	0.90
AEN significance (`astrometric_excess_noise_sig`)	16.5

An elevated RUWE (commonly RUWE $\gtrsim 1.4$) indicates a poor fit of the 5-parameter single-source astrometric model and is often associated with unresolved binaries, blends, or other astrometric complexity. The parallax is poorly constrained and we therefore do not adopt a Gaia-only geometric distance.

A major forensic update is that Gaia DR3 resolves a close neighbor at a separation $\rho \simeq 0.688''$ with $\Delta G \simeq 2.21$ mag. This neighbor lies within the DESI $1.5''$ fiber aperture and must be treated as a potential blend contaminant.

2.4. *Additional surveys*

The multi-wavelength validation uses WISE/2MASS photometry, GALEX NUV imaging, TESS full-frame-image photometry, ZTF multi-year g, r photometry, Legacy Survey imaging cutouts, ROSAT/XMM/Chandra X-ray catalogs, and NVSS/FIRST/VLASS radio surveys.

3. RV VARIABILITY METRICS

3.1. *Single-target RV statistics*

For each target with N RV epochs we define the maximum observed RV span:

$$\Delta\mathrm{RV}_{\max} = \max_i (\mathrm{RV}_i) - \min_i (\mathrm{RV}_i) . \quad (1)$$

Table 2. Definitions for Equation (1).

Symbol	Meaning
RV_i	Radial velocity at epoch i (km s^{-1})
$\Delta\mathrm{RV}_{\max}$	Maximum RV span across all epochs (km s^{-1})
$\max_i(\cdot)$	Maximum over epochs indexed by i
$\min_i(\cdot)$	Minimum over epochs indexed by i
N	Number of RV epochs
i	Epoch index (integer)

To quantify the significance of variability we define:

$$S = \frac{\Delta\mathrm{RV}_{\max}}{\sqrt{\sum_{i=1}^{N} \sigma^2_{\mathrm{RV},i}}}. \quad (2)$$

Table 3. Definitions for Equation (2).

Symbol	Meaning
S	Global RV-variability significance (dimensionless)
$\Delta\mathrm{RV}_{\max}$	Maximum RV span (km s^{-1})
$\sigma_{\mathrm{RV},i}$	RV uncertainty at epoch i (km s^{-1})
$\sum_{i=1}^{N}(\cdot)$	Sum over epoch index i from 1 to N
N	Number of RV epochs
i	Epoch index (integer)
$\sqrt{(\cdot)}$	Square-root operator

3.2. *Leave-one-out robustness and leverage*

We compute a leave-one-out significance $S^{(-k)}$ by excluding epoch k and recomputing Equation (2). We then define:

Table 4. Definitions for Equation (3).

Symbol	Meaning
$S^{(-k)}$	Significance S recomputed with epoch k excluded (dimensionless)
k	Index of excluded epoch (integer)
$S_{\min,\mathrm{LOO}}$	Minimum of $S^{(-k)}$ over all k (dimensionless)
S_{robust}	Conservative robustness statistic (dimensionless)
S	Global RV-variability significance from Equation (2)
$\min(\cdot)$	Minimum operator
N	Number of RV epochs
$1 \le k \le N$	Range of k values included in the minimum

$$S_{\min,\mathrm{LOO}} = \min_{1\le k\le N} S^{(-k)}, \qquad S_{\mathrm{robust}} = \min\left(S,\, S_{\min,\mathrm{LOO}}\right). \quad (3)$$

We also define a leverage statistic:

$$d_i = \frac{\left|\mathrm{RV}_i - \overline{\mathrm{RV}}\right|}{\sigma_{\mathrm{RV},i}}, \qquad d_{\max} = \max_i d_i, \quad (4)$$

where $\overline{\mathrm{RV}}$ is the inverse-variance-weighted mean RV.

Table 5. Definitions for Equation (4).

Symbol	Meaning
d_i	Leverage of epoch i (dimensionless)
RV_i	Radial velocity at epoch i (km s^{-1})
$\overline{\mathrm{RV}}$	Inverse-variance-weighted mean RV (km s^{-1})
$\sigma_{\mathrm{RV},i}$	RV uncertainty at epoch i (km s^{-1})
$\lvert\cdot\rvert$	Absolute-value operator
$d_{\max}$	Maximum leverage over all epochs (dimensionless)
$\max_i(\cdot)$	Maximum over epochs indexed by i

4. NEGATIVE-SPACE VALIDATION PIPELINE

For each RV-variable candidate we apply a multi-wavelength filter designed to select systems with strong gravitational evidence for a companion but little corresponding light. Key checks include Gaia astrometry/duplicity (including explicit neighbor searches), WISE/GALEX constraints, TESS/ZTF photometry, deep imaging, and X-ray/radio catalog searches.

5. CASE STUDY: GAIA DR3 3802130935635096832

5.1. *DESI per-epoch RVs and extreme variability*

Table 6. DESI DR1 per-epoch catalog RV measurements for Gaia DR3 3802130935635096832.

Epoch	Source	MJD	Date (UT)	RV $\pm\sigma_{\rm RV}$ (km s^{-1})
1	DESI	59568.488	2021-12-20	-86.39 ± 0.55
2	DESI	59605.380	2022-01-26	$+59.68 \pm 0.83$
3	DESI	59607.374	2022-01-28	$+26.43 \pm 1.06$
4	DESI	59607.389	2022-01-28	$+25.16 \pm 1.11$

The maximum catalog RV span is $\Delta{\rm RV}_{\rm max} \approx 146$ km s^{-1} over 38.9 days. Using DESI DR1 formal uncertainties, a constant-RV model is rejected at $\Delta\chi^2 \approx 2.7 \times 10^4$ (DESI-only). Two exposures on the same night are consistent in the *catalog* to within ~ 1 km s^{-1}. However, later per-exposure forensic analysis shows that wavelength-dependent instability can bias the catalog solution without necessarily creating large *intra-night* catalog inconsistencies (i.e. both same-night exposures can be biased in the same direction).

5.2. *Blend constraint from ΔG*

The Gaia-resolved neighbor has $\Delta G \simeq 2.21$ mag. The corresponding G-band flux ratio is:

$$b_G = 10^{-0.4\Delta G}. \quad (5)$$

Table 7. Definitions for Equation (5).

Symbol	Meaning
b_G	Flux ratio in Gaia G (neighbor/primary; dimensionless)
ΔG	Gaia G magnitude difference (neighbor minus primary; mag)
$10^{(\cdot)}$	Base-10 exponential operator
0.4	Magnitude-to-flux conversion constant ($0.4 = 1/2.5$)

With $\Delta G \simeq 2.21$, $b_G \simeq 0.13$. Because the neighbor is close and likely redder, the effective flux ratio can be larger in the redder DESI Z arm than in G.

5.3. *Per-exposure, per-camera forensic resolution of Z-arm instability*

Motivated by earlier arm-split pathologies in coadded products, we downloaded per-exposure DESI `cframe` products for EXPIDs 114768, 120194, 120449, and 120450 and remeasured RVs by wavelength region. We (i) renormalize formal uncertainties by the reduced chi-squared χ^2_ν of the best-fit template model to account for underestimated noise and template mismatch, and (ii) estimate RV uncertainties using a curvature-based $\Delta\chi^2 = 1$ criterion rather than assuming a fixed RV error floor.

Same-night exposures (120449 and 120450; 15 minutes apart) show:

- Full Z arm yields a ~ 34 km s^{-1} discrepancy between exposures.
- Restricting to the Ca II triplet window (8500–9000 Å) reduces the discrepancy to ~ 2.8 km s^{-1}, i.e. a $\sim 12\times$ improvement relative to full-Z.
- Wavelength splitting within Z indicates that the sky-dominated 9000–9800 Å region is unstable, while the Ca II triplet region is stable between same-night exposures.

These results identify a concrete instrumental failure mode (sky-dominated red-end instability) that can bias DESI DR1 RVs for faint, red stars, while simultaneously providing an empirically validated "trusted" spectral window for more conservative RV inference.

5.4. *Trusted-window RV curve (Ca II triplet, 8500–9000 Å)*

We define the Ca II triplet window (8500–9000 Å) as a trusted window for RV inference. Table 8 reports per-exposure RVs derived using only this window (values and uncertainties from the trusted-window pipeline outputs).

The trusted-window RV swing between the most extreme exposures is $\Delta{\rm RV} \approx 151.2$ km s^{-1} (from -85.6 to $+65.6$ km s^{-1}), consistent with and slightly exceeding the catalog-scale swing. Notably, the same-night pair is systematically higher in the trusted window than in the catalog by ~ 25 km s^{-1}, consistent with the catalog solution being pulled by the unstable sky-dominated red end of the Z arm.

5.5. *Same-night residual discrepancy and systematic floor*

Although the trusted window dramatically improves stability, the same-night exposures differ by $\Delta{\rm RV} \approx 2.8$ km s^{-1}. The curvature-based uncertainties in Table 8 are $\lesssim 0.4$ km s^{-1} per exposure, implying that this same-night difference is formally significant. However, the reduced chi-squared values in the trusted window remain $\chi^2_\nu > 1$ (typically $\sim$ 2–8), indicating residual

Table 8. Per-exposure RVs from the trusted window (Ca II triplet, 8500–9000 Å).

EXPID	MJD	Trusted RV	$\sigma_{\rm trusted}$	χ^2_ν	Catalog RV	Trusted − Catalog
114768	59568.488	−85.6	0.38	5.3	−86.39	+0.8
120194	59605.380	+65.6	0.40	6.8	+59.68	+5.9
120449	59607.374	+53.1	0.36	2.0	+26.43	+26.7
120450	59607.389	+50.3	0.31	7.5	+25.16	+25.1

NOTE—$\sigma_{\rm trusted}$ denotes the trusted-window RV uncertainty per exposure (km s^{-1}) computed via a curvature-based $\Delta\chi^2 = 1$ method after uncertainty renormalization by χ^2_ν.

template mismatch and/or remaining systematics. We therefore interpret the same-night residual as evidence for a *few km s^{-1} systematic floor* in windowed DESI RVs for this blended M-dwarf target, even in the trusted Ca II window.

5.6. *Conservative semi-amplitude bound*

Using the trusted-window RV span, we define the minimum implied RV semi-amplitude:

$$K_{\rm min} = \frac{\Delta {\rm RV}_{\rm trusted}}{2}, \tag{6}$$

where $\Delta{\rm RV}_{\rm trusted}$ is the maximum trusted-window RV span.

Table 9. Definitions for Equation (6).

Symbol	Meaning
$K_{\rm min}$	Minimum implied RV semi-amplitude (km s^{-1})
$\Delta{\rm RV}_{\rm trusted}$	Trusted-window RV span (km s^{-1})
2	Numerical factor converting peak-to-peak span to semi-amplitude

With $\Delta{\rm RV}_{\rm trusted} \approx 151.2$ km s^{-1}, we obtain $K_{\rm min} \approx 75.6$ km s^{-1}. Because the DESI cadence is sparse and may not capture true extrema, the true semi-amplitude can exceed $K_{\rm min}$.

6. PHOTOMETRIC, INFRARED/UV, X-RAY AND RADIO CONSTRAINTS

TESS photometry shows no deep eclipses or large coherent modulation. ZTF photometry places limits on large-amplitude rotational modulation, disfavoring purely activity-driven explanations for a ~ 150 km s^{-1} swing. WISE colours ($W1 - W2 \simeq 0.05$) show no strong IR excess. GALEX NUV non-detection disfavors a hot WD companion. No significant X-ray or radio counterpart is found in major catalogs, consistent with a non-interacting (quiescent) system.

7. LIMITATIONS

The system remains unconfirmed due to:

1. Sparse DESI cadence (four epochs; two nearly simultaneous) and intrinsic period aliasing.
2. Confirmed close neighbor inside the fiber: blend-aware inference is mandatory.
3. Residual systematics at the few km s^{-1} level persist even in the trusted window, and template mismatch remains evident via $\chi^2_\nu > 1$.
4. LAMOST RVs are not decisive due to internal inconsistencies across extraction methods.
5. Gaia RUWE/AEN are elevated but are not uniquely attributable to orbital wobble given duplicity.

8. CONCLUSIONS

Gaia DR3 3802130935635096832 is an extreme DESI DR1 RV variable with a large catalog RV swing and a "darkness" profile (no strong IR/UV excess, no large photometric modulation, no cataloged X-ray/radio counterpart). Gaia DR3 confirms a close neighbor at $\rho \simeq 0.69''$, motivating blend-aware analysis.

Per-exposure, per-camera validation identifies the sky-dominated red end of the Z arm (9000–9800 Å) as the source of previously observed instability; restricting to the Ca II triplet window yields a trusted-window RV curve with a ~ 151 km s^{-1} swing, consistent with the catalog-scale variability, while improving same-night stability from ~ 34 km s^{-1} (full Z arm) to ~ 2.8 km s^{-1} (Ca II window). The trusted-window analysis also explains why the DESI catalog RVs for the same-night pair were biased low by ~ 25 km s^{-1}.

We therefore retain this system as a *strong but unconfirmed* dark compact companion candidate. The highest-value next step is high-resolution spectroscopy and/or high-angular-resolution imaging to separate the blended components and convert the large RV swing into a definitive dynamical mass constraint.

9. DATA AND CODE AVAILABILITY

All scripts, configuration files, diagnostic plots, and machine-readable results used in this work are publicly available at https://github.com/simulationstation/DESI-BH-CANDIDATE-SEARCH.

Software: DESI DR1, Gaia DR3, LAMOST, TESS, ZTF

Facilities: DESI, Gaia, LAMOST, TESS, ZTF